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MODERATE-COST APPROACHES FOR HYDRODYNAMIC TESTING OF HIGH PERFORMANCE SAILING VESSELS

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This study examines the relative merits of physical testing techniques which may be used in early stage design for assessment of the resistance of high-performance sailing vessels. The hull chosen as a benchmark form is a high-speed hard-chine sailing dinghy. The hull proportions and shape are typical of modern trends in skiff design, but may also be considered to be broadly similar to some high performance yacht hulls. The 4.55m hull was tested at full scale in a moderate size towing tank, at 1:2.5 scale in the same tank, and at full-scale by towing on open water.

Results show the mean discrepancy in the measured resistance between the open water towing and the full-scale tank test is around 4%. The challenges of full-scale open-water testing are discussed and several improvements identified for future work. Comparison of the full-scale results suggests that blockage and depth correction for the full-scale hull in the tank do not present a substantial problem for subcritical speeds. Larger discrepancies were found between resistance from the model scale and the full scale tank tests at higher speeds; it was speculated that these discrepancies relate to the differences in the detailed geometry of the model and full-scale boat, particularly in the region of the chines.

1 INTRODUCTION

Large-scale tank testing at high speeds inevitably requires the use of a large, and hence costly, towing tank, which in some cases may cost many thousands of Euros per day. In many sailing vessel design applications the cost of such a test campaign will be difficult to justify, especially at the early design stages. The present study explores the relative merits of three different moderate-cost approaches to physical measurement of the resistance of high performance sailing vessels by directly comparing results obtained for the same hull design using these approaches. These involve testing:

a) a moderate-scale model in a moderate-scale test tank,
b) a large (or full) scale model in a moderate-scale test tank,
c) a large (or full) scale model by towing behind a powerboat on open water.

In the present study all tank tests were carried out in the towing tank of the Kelvin Hydrodynamics Laboratory at the University of Strathclyde in Glasgow. The tank is 76m long, 4.6m wide and 2.5m deep, with a typical water depth of 2.1m. The carriage is capable of speeds of up to 4.6 m/s. The towing system is entirely conventional, with the model free to heave, pitch and roll, and constrained in surge, sway and yaw. In the tests described here, the resistance was measured using a strain gauge load cell, while sinkage and trim were measured using linear variable displacement transducers (LVDTs). This can be regarded as fairly typical of a moderate-scale test tank.

The vessel chosen is a high-performance single-handed sailing dinghy known as a Musto Skiff (see Figure 1). The hull form is typical of a modern skiff form with an overall length of 4.55m, a single chine, and relatively flat sections between the keel and chine and between the chine and deck edge. The dinghy has a relatively large full-battened mainsail with an area of 11.08m^2 and an asymmetric spinnaker of 15.50m^2. The all-up weight of the boat in sailing condition is 82.5kg; the powerful rig combined with light weight allows speeds of over 20 knots.

The displacement condition in the present study assumes an 80kg sailor wearing 5kg of clothing. The key details of the boat are shown in Table 1. This table assumes the boat is trimmed so that the chine is level; this represents a typical sailing condition in moderate wind strengths. More details of the design can be found on the class website (www.mustoskiff.com). For vessels of the size of sailing dinghies, it is possible to test at full-scale; the results of such tests may inform dinghy designers as well as researchers wishing to assess and improve performance prediction approaches such as velocity prediction programs (VPPs).

However, an additional application is also considered to be of interest here: the Musto Skiff was chosen because the hull proportions as well as the hull-form shape of the boat are broadly similar to some modern high performance maxi yachts. Hence a full-scale Musto Skiff, as well of being of interest in itself, can also be regarded as generally representative of a large-scale model of a high performance maxi yacht, and a moderate-cost approach to large-scale model testing of high performance yachts could be of interest to yacht designers at the early concept design stage if it could be shown to be sufficiently accurate.

Figure 1 The Musto Skiff

The key challenges of the different possible approaches and the details of the methodology adopted in each case are discussed in the following sections.

Table 1 Musto Skiff Main particulars

Displacement	167.5	kg
WL Length	4.500	m
WL Beam	0.941	m
Draught	0.127	m
Wetted Area	3.080	m^2
Max section area	0.060	m^2
Waterplane Area	2.903	m^2
Prismatic coefficient	0.622	
Max Section area coefficient	0.591	
Waterplane area coefficient	0.686	
LCB from midships (+ve fwd)	-7.639	% Lwl
LCF from midships (+ve fwd)	-11.615	% Lwl

2 MODERATE-SCALE MODEL TESTING IN A MODERATE-SCALE TEST TANK

2.1 INTRODUCTION

Model testing in a moderate-scale towing tank is of course the most conventional approach to moderate-cost testing of a high performance hull. The methodology both for testing and extrapolation is well-established and set out through procedures established by bodies such as the ITTC Resistance Committee, and the equipment required is essentially standard. However relatively few tank tests of scaled sailing dinghies, and in particular, tests of this type of skiff hull have been published.

Day and Nixon (1) tested a model Laser dinghy at a scale of 0.48; however the Laser has a conventional moderate performance hull, and the testing challenges are rather different from a high performance skiff. A two-person skiff design, the Aura, was tested at the Universities of Strathclyde and Newcastle in 2012 (see (2)) as a 1/4 scale model of length 1.19m, and all-up weight of 3.5kg. The tests described by Viola and Enlander in (2) focussed on the effect of trim on resistance at model scale.

2.2 MODEL SIZING

It is well-known that the use of a smaller scale model (i.e. larger scale ratio) allows higher full-scale speeds to be achieved, while model making costs will often be less than the equivalent costs for larger models (though not necessarily in proportion to size). Once models become sufficiently small, model weight starts to become a challenge, and different manufacturing technologies may be required, pushing up costs: for example the Aura model, built by Ovington Boats, was built in carbon fibre from a CNC-milled mould in order to achieve the model weight of 1.8kg.

By choosing the model size to “fit” the tank, the blockage ratio (defined as the maximum section area of the boat / cross section of the tank) may be kept within a range typical of modern tank-testing practice, and therefore can be regarded as amenable to accurate correction. However many blockage correction approaches generally recommended have been derived for conventional ships and may not be reliable for high speed planing vessels. The ITTC procedure 7.5-02-05-01 “Testing & Extrapolation Methods: High Speed Marine Vehicles: Resistance Test” (3) quotes several simple guidelines for assessing whether blockage is likely to be an issue for planing hulls, without giving details of references. The key rules identified by the ITTC can be summarised as: tank width should be greater than seven times the tank width (due to Savitsky) and tank width should be greater than two times the model length (due to Muller-Graf).

A second problem which may occur in moderate-scale tanks at high speeds, even with a scale model, is the influence of water depth, particularly on wave-pattern resistance, especially when depth Froude numbers approach unity, since the wave pattern resistance may vary substantially at high sub-critical, trans-critical and super-critical depth Froude Number. The same ITTC procedure quotes a simple rule due to Muller-Graf which states that the tank depth should be greater than 0.8 times the model length. This seems very simplistic, since it is perfectly possible (and quite likely for a boat of this performance) to achieve high depth Froude numbers whilst still satisfying this rule.

In the present study the approach of Tamura is applied as suggested in the ITTC procedure for resistance tests for conventional ships (4). This is not specifically intended for high speed vessels, but does include a simple correction for finite depth effect. However the form of the correction suggests it should not be used for trans-critical or supercritical depth Froude Number tests. There are several challenges related to extrapolation which may be of particular interest in this context. The first is that of turbulence stimulation. Conventional approaches such as those recommended by the ITTC involving the use of studs, trip wires, or sand strips have been validated for large models of low-speed ships, but may be less reliable for high–speed vessels. As models become smaller the ITTC recommendations for stud size, separation, and location appear increasingly unsuitable as the number of studs reduces to single figures, and the studs become relatively large compared to the hull, requiring stud drag correction (see for example Day et al. (5)). Different approaches to turbulence stimulation may thus be required.

A particular challenge occurs with planing vessels for which the forward extent of the wetted length varies substantially with speed, so that turbulence stimulation cannot be in the correct location for the whole speed range unless the stimulation device is moved as speed is varied. An alternative approach was used by Viola and Enlander (2) in which a probe is towed forward of the model in order to stimulate turbulence in the onset flow. This has the disadvantage of generating some small waves in the otherwise still water which can add significantly to the resistance. The effect of waves is discussed in section 5.1. Some insight into the challenges may be gained from a study of turbulence stimulation for high-speed slender catamaran ferries through a series of geosim tests (Bertorelli et al. (6)); one conclusion drawn was that tests with models smaller than about 2.0m the resistance could not be considered reliable even where detailed corrections for stud drag were considered. However with models larger than 2.0m it was concluded that turbulence stimulation was not required.

A second challenge relates to the wetted area used to estimate the viscous resistance. This can vary substantially when the boat is planing (as shown in Figure 1), and considerable extra effort is required to estimate the running wetted area, using underwater cameras, paint techniques or other technology. Use of the static wetted area in cases for which the wetted is reduced due to planing will lead to an overestimation of the viscous resistance at model scale and hence incorrect extrapolation of the viscous and wave pattern components.

A final challenge relates to the form factor; for a skiff hull such as the Musto Skiff with an immersed transom, the standard Prohaska test at normal sailing trim may be unreliable, since the transom will be "wet" at the low speeds of the Prohaska test but "dry" at sailing speeds. Hence the flow in the Prohaska test is not representative of the flow in the sailing condition. This may be addressed by conducting the Prohaska test with the vessel trimmed bow-down so that the flow detaches smoothly from the transom (see Couser et al. (7)); however this has the disadvantage that the displaced shape of the hull does not correctly represent the sailing condition.

2.3 PRESENT STUDY

In the present study the model-scale tank tests were conducted using a model constructed at a scale of 1:2.5, yielding a model of overall length of 1.82m. This size was a compromise, allowing a good range of full-scale speeds, whilst being close to meeting the suggested criterion for minimum length suggested by Bertorelli (6). The model easily met the various criteria for blockage as described above, with tank width > 12×Bwl (compared to ITTC target of 7×Bwl), tank width > 2.5×Lwl (compared to target of 2×Lwl), and tank depth >1.1×Lwl (compared to target of 0.8×Lwl).

In the first instance it was originally intended to build the physical model from a CAD model generated from measurements from the full-scale dinghy. These measurements were made using a Qualisys optical motion capture system. The model generated from this process was used in the initial analysis of the full-scale data. However, the Musto Skiff builders later kindly supplied a lines plan for the boat, and the CAD model used to build the physical model was generated from this plan (see Figure 2).

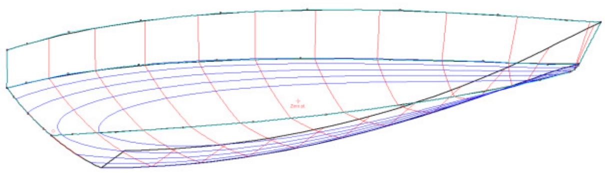

Figure 2 Final CAD model generated

It is interesting to note that the model-scale boat was very similar, but not completely identical, to the full-scale boat. The model was not made with a daggerboard slot, while the full-scale boat had the daggerboard slot plugged with foam, so there are some minor differences in this region of the boat. In some areas (e.g. the sheer-line & the transom profile) the differences were above both static and running waterlines, and thus had little or no impact on the hydrodynamics. Other modifications, including the incorporation of a small radius on the chine line of the production boat, which was sharp in the model, and a minor change to the forefoot profile, may have been made to ease challenges associated with moulding the production boat. The possibility of impact of these changes is discussed further in section 5.3.

The model was towed from a point corresponding to the mast step on the full-scale boat; this was chosen to allow direct comparison with the full-scale tests, in which the mast step provided a convenient and strong attachment point. No appendages were used in the model-scale testing. The scale ratio allowed testing at full-scale speeds of up to 7.25 m/s or just over 14 knots, although the limitations of the blockage correction reduced the maximum speed to 13 knots. This is adequate for upwind sailing in the Musto Skiff, but rather slow for downwind sailing in stronger winds. The blockage ratio was 0.11%, which can be regarded as very small. Figure 3 shows the model in the tank.

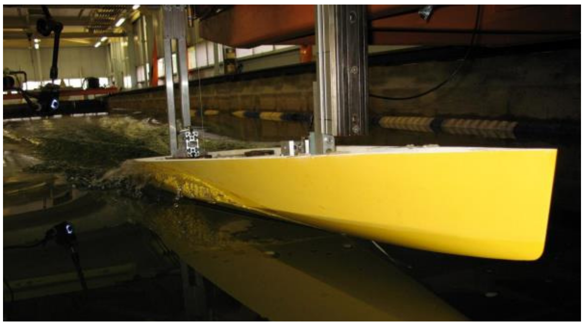

Figure 3 Scale Model in Tank

The baseline displacement and trim condition for all three test modes was the same; the model was ballasted to a (full-scale) displacement of 167.5kg corresponding to an all-up boat weight of 82.5kg plus a crew of weight 80kg wearing 5kg of clothing. The boat was then trimmed so that the transom was just touching the water. This approach had been adopted by Day and Nixon (1) in model tests of a Laser dinghy. This trim is quite typical for a Laser over a fairly wide speed range and was adopted for the first sets of tests conducted in the present study — which were the full-scale tests. It was subsequently found that this trim was appropriate for relatively low speeds and light winds (as noted in the training DVD for the Musto Skiff (Stenhouse (8))) but that it was rather “bow-down” for a Musto Skiff compared to best sailing practice in moderate winds. Nonetheless it was retained as the benchmark case for the model tests in order to allow comparison with the full-scale tests.

3 LARGE/FULL-SCALE MODEL TESTING IN MODERATE-SCALE TEST TANK

The key advantage of larger scale testing in both yacht and dinghy applications is the reduced demand on extrapolation from a large scale model (or full-scale dinghy) compared to a moderate-scale test, and for full scale testing in particular, no issues related to turbulence stimulation or wetted area estimation. In the application to sailing dinghy testing there are further advantages in that building a full-scale boat eliminates the need to build a dedicated model at all, as the full-scale boat may also be used for sailing trials. Furthermore, adding appendages (e.g. daggerboard & rudder) may well be easier in a large model or full scale boat than in a smaller model.

The typical disadvantage of testing the larger scale model is the need for use of a larger (and hence typically more expensive) tank. Several studies have examined sailing dinghies at full scale in test tanks (generally large commercial tanks). Some have been aimed at supporting Olympic campaigns and as a result studies have not been published other than via press releases. Levin and Peters (9) report a campaign of tests of a full-scale Laser Dinghy at the SSPA towing tank (260m×10m×5m) in Gothenburg; however their work focusses on CFD simulation and relatively few details of the tests are presented. Beaver and Zseleczky (10) report a set of tests on an early foiling Moth dinghy at full scale in the USNA Hydromechanics Lab test tank (116m×7.9m ×4.9m). These tests focussed more on the foiling performance than the displacement mode. In both cases the sizing of the hull relative to the tank was relatively conventional.

In the present study a standard Musto Skiff was tested in the Kelvin Hydrodynamics Laboratory tank. These were the first tests carried out in the present study. In this case the hull is much larger relative to the tank than would be considered usual. In order to avoid damaging the boat, the towing post was attached via a custom fitting at the mast step (as in the scale model test); the yaw guide was fitted on the bow, via a post attached to the bowsprit fitting, rather than in the conventional position on the stern, but otherwise the test set-up was conventional. In spite of the length and beam of the boat, the blockage area ratio was still only 0.7%, which is within the range which would be considered acceptable for correction for a conventional ship. However the tank width is 4.86×Bwl (compared to target of 7), 1×Bwl (compared to target of 2×) and tank depth is 0.44×Lwl (compared to target of 0.8×). Hence the full-scale boat violates all of the guidelines for blockage. The maximum speed is limited in practice by the requirement to maintain sub-critical depth Froude numbers to 4.5 m/s, or just less than 9 knots.

The hull was ballasted to the sailing weight of 167.5kg, and trimmed as described in the previous section so that the transom was just touching the water. No daggerboard was used, and the daggerboard slot was fitted with a divinycell foam plug. Since it was expected that the open water tests might require the use of a rudder, towing tests were carried out both with and without the rudder fitted. This led to identification of an error in the process. The model had been ballasted to the target weight displacement neglecting the displaced volume of the rudder and daggerboard. In practice it was found that the rudder was found to be positively buoyant, and therefore when fitting the rudder, in order to maintain consistent underwater shape of the hull, an additional mass was added to the rudder to correct for the buoyancy.

Figure 4 Full-scale Musto Skiff in Tank

If the results were being used for accurate assessment of the performance of the hull, then a correction should be made to the assumed weight to allow for the “missing” buoyancy of the appendages. However the same assumption was made for all tests, so the comparison between results is still valid. An additional short set of tests was carried out in order to estimate the magnitude of the impact on the resistance of waves in the open water testing.

4 OPEN WATER TOWING TESTS

The third option for moderate-cost testing, and especially where no tank is available, is to test the hull on open water, by towing a large-scale model (or full-scale dinghy) behind a powerboat. This gives the advantage of no blockage or depth effects if deep water is used, and of course, no tank costs. A number of well-known testing institutions use open-water testing for large scale model testing of manoeuvring characteristics of commercial ships, and there is increasing interest in the use of large-scale self-propelled radio controlled models for manoeuvring and sea-keeping studies of high-performance powerboats. The challenges of open-water resistance testing are rather different however, since the level of accuracy expected for resistance measurements is generally high, requiring very accurate force and speed measurements, and very calm water.

Carrico (11) towed a full-scale Laser dinghy on a canal in New Orleans, with the Laser positioned to one side of the powerboat, at speeds of up to eleven knots, measuring speed (using a handheld GPS) , resistance (using a load cell), and trim (using an electronic inclinometer). The yaw angle was controlled using two guidelines attached to the towing boat, which allowed the yaw angle to be controlled without the use of a rudder.

Watin (12) presented a study addressing a number of aspects of the refinement of the design of the well-known Olympic 49er two-man skiff dinghy for the 2008 Beijing Olympics. A substantial part of the study addressed towing of two 49ers from a power boat in Sydney Harbour; the use of two boats allowed comparative studies to be made. The set-up is shown in Figure 5. Both boats were steered, and so the drag values included the drag of the rudder; and the ballast weight included the weight of the crew.

Figure 5 49er Open Water Towing tests (from Watin (2007))

Speed was measured using a GPS, resistance was measured using a load cell, and heel and trim were set visually using marks on the hull.

Following the study of Watin, and in a precursor to the present study, students at the University of Strathclyde towed a Laser and later a Solo dinghy and measured the resistance (see Figure 6). This generated valuable experience in addressing the numerous practical challenges of conducting the tests. The data from the Laser towing was compared to model tests of the Laser from Day and Nixon (1); the comparison gave sufficient encouragement that the results were reasonable, and could be improved to give worthwhile data.

The towing tests for the present study were carried out at Bardowie Loch located just north of Glasgow. This small loch is sheltered in many wind directions, and allowed a test run length of around 500m. The towing boats used were RIBs borrowed from the sailing club based at Bardowie Loch. For the first few tests a relatively large Rigid Inflatable Boat (RIB) was used with a 50HP outboard engine. It was later found that better results were achieved with a smaller RIB with a 25HP engine, since the extra power was not needed, speed regulation was better, and the boat created less wake.

In the previous open water towing studies at Bardowie, the dinghy had been towed a long distance behind the tow boat rather than to one side as in the tests of Watin. It is relatively difficult to attach a towing “mast” arrangement such as that used by Carrico (11) or Watin (12) to a RIB, due to the lack of strong attachment points. The authors were also concerned that the towed dinghy/model would be affected by the bow wave of the towing boat in the side by side arrangement; naturally these waves are largest close to the bow.
Set against this, in a “straight” tow, towing the dinghy behind the towboat leaves the dinghy in the transverse wave pattern of the towboat. This effect may be reduced by towing on a long line, since the transverse waves decrease in amplitude approximately with the square root of the distance from the towboat. A very lightweight dyneema line of approximately 50m in length and 0.9mm diameter was used to tow the dinghy. This was light enough not to drag in the water due to self-weight over the range of speeds tested. The line was marked so that the length was repeatable between tests.

The speed was measured using a VBox 3i system. This is a GPS-based system originally intended for measuring speeds of race cars, but increasingly widely adopted for maritime use. The system uses the Doppler shift in the GPS carrier data to measure the speed and heading data, at 100Hz, with mean accuracy of 0.028m/s. The system can be used to log analogue data via an A/D converter, as well as allowing connectivity via a CAN bus interface. A 2DOF load cell was used which allowed simultaneous measurement of resistance and side force. This was mounted on a short mast located on the mast step, and supported by rope to the chain plates. The use of a 2DOF load cell allowed estimation of the towing angle, which could be used to assess when the dinghy was correctly following the towboat. The mast was also used to mount an anemometer and wind vane. The tow line passed through the spinnaker chute mouth to the tow boat.

The VBox was located on the Musto¸ since it proved more convenient to site the load cell at the dinghy end of the tow-line rather than the towboat end in order to remove the need for any cabling between the towboat and dinghy. For this reason a Speedpuck stand-alone GPS speed system was used as a visual guide for the towboat driver. In case of any accidents, the VBox was mounted in a waterproof case along with the battery pack and the strain gauge amplifier (see Figure 7). It was originally intended to include an inclinometer with the system to measure trim, but this proved difficult to power from the battery pack, and hence was not deployed in the end. A 6-DOF IMU (part of the VBox system) was installed, and was used to make a rough estimate of trim, but was not particularly accurate. Instrument calibration was checked at the beginning and end of every day.

The procedure adopted for the testing was to do pairs of runs in opposite directions upwind and downwind (relative to the very light winds on the testing days) in order to try and eliminate any effects due to atmospheric wind (see Figure 8). For each run, the VBox was started with the dinghy directly behind the towboat, and a timer started to allow subsequent cross checks to be made. The towline was paid out slowly until the 50m length was all out, and the towboat then accelerated gradually to the target speed. One person drove the towboat monitoring speed and heading, whilst a second person watched the dinghy to ensure that it was following behind the towboat. At the end of the run the towboat would decelerate slowly and the towline would be reeled in so that the dinghy could be turned around and the reverse run started.

It was attempted to tow the boat without the rudder in the hope that the hard chine form would prove more directionally stable than the Laser had been. This did not prove to be the case, and without the rudder the boat "fishtailed" from side to side, eventually leading to breakage of the towline. The rudder was then fitted and fixed central with an elastic tie. Some trials were made with a third crew member steering the boat, but it proved difficult to guarantee repeatable heel and trim. However for future tests this may become necessary.

The ultimate limitation on the speed of the tests proved to be when the results became unreliable due to the increasing wake of the towing boat (see Figure 9). However it did prove to be possible to replicate the range of speeds achieved in the tank tests. Solutions to some of the practical issues identified are discussed in section 0.

Figure 6 Towing of Solo dinghy in previous tests

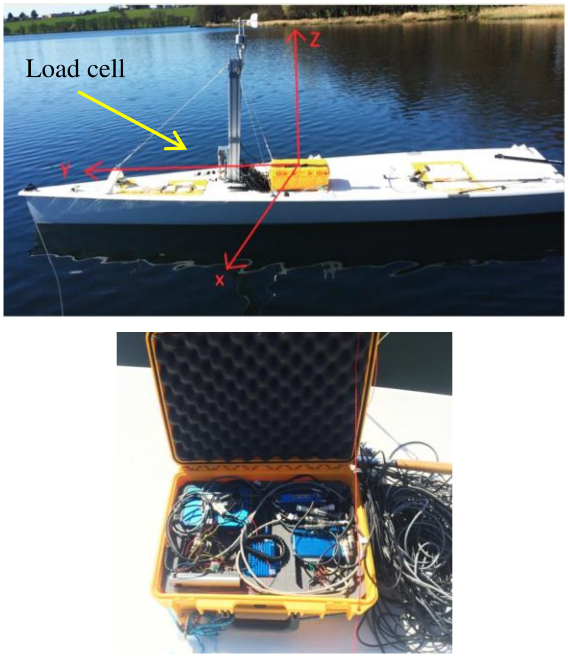

Figure 7 Instrumentation set-up for present tests

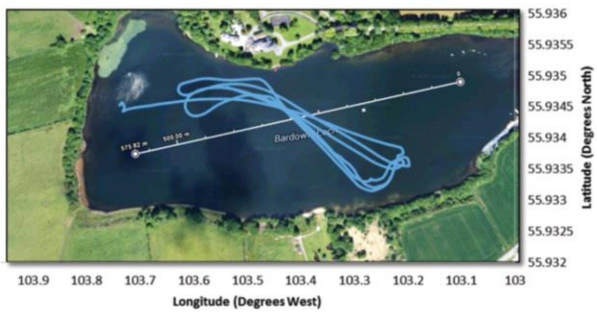

Figure 8 Typical track of runs: Runs 009-014

Figure 9 Aerial View of tests

5 RESULTS

5.1 FULL-SCALE TANK TESTS

The full scale tank results require minimal re-processing. The resistance results are adjusted to reflect a constant water temperature of 12.5 degrees (which was similar in the test tank and the loch) and the Tamura blockage correction is applied where shown. Results for the resistance are shown in Figure 10. This shows the increasing influence of the blockage correction at the higher speeds as the depth Froude number approaches unity. A complete uncertainty analysis of the data has not been carried out at this stage. However as an indication of the repeatability of the results, a set of five repeats was carried out at a speed of 3.342m/s. The standard deviation of the resistance over the five repeats was found to be 0.33% of the mean value.

Figure 11 shows the effect of the rudder on the total resistance. Whilst the effect is small, the trend displays some unexpected behaviour. Initially the delta due to the rudder increases roughly as might be expected; however there is a sudden drop in the region between 3.0 and 3.5 m/s. Some insight into this phenomenon may be gained by examining the trends in the trim and sinkage of the boat, shown in Figures 12-13. It can be seen that the trim angles and sinkage values are almost identical up to 3.0 m/s but start to diverge around 3.0m/s. The boat starts to adopt bow-up trim around 2.75 m/s, and exhibits around one degree of bow-up trim at around 3.25 m/s. The trim angles start to diverge at that point, along with the sinkage, and it is assumed that this effect, possibly due to the buoyancy of the rudder, which causes the complex behaviour in resistance.

A final set of tests examined the effects of small waves on the resistance. The aim was to estimate the magnitude of any error due to small waves in the open water testing.

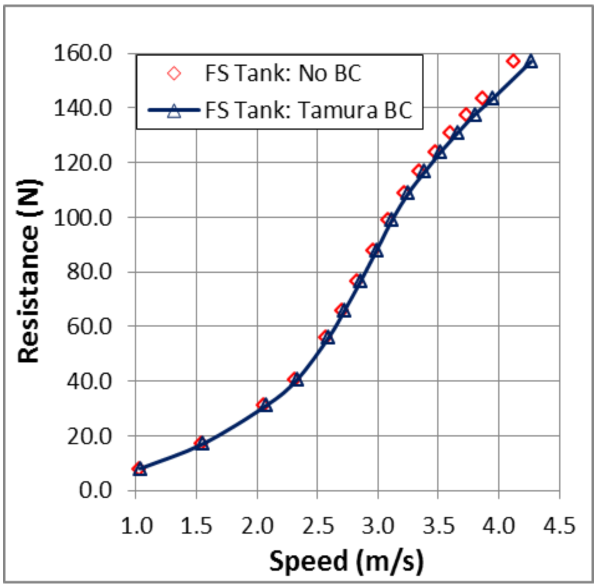

Figure 10 Full scale Tank Tests: Effect of Blockage Correction

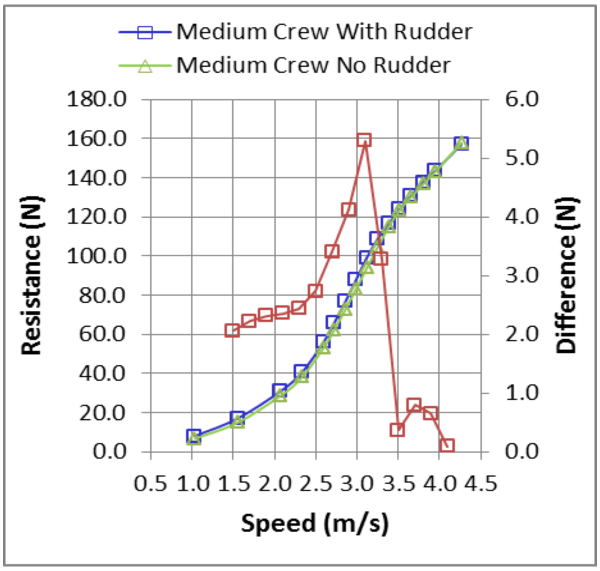

Figure 11 Effect of Rudder on resistance

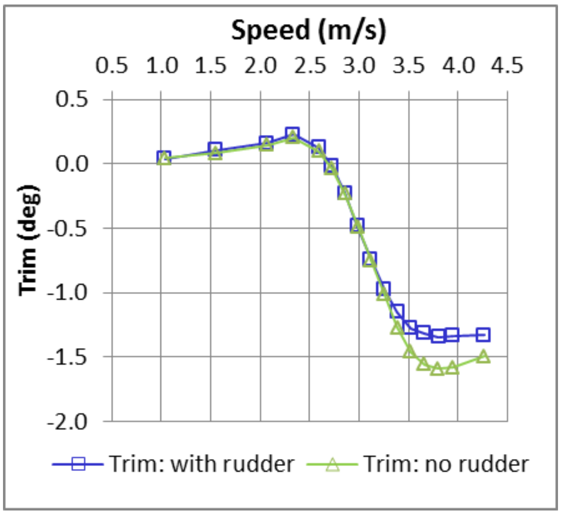

Figure 12 Effect of rudder on trim

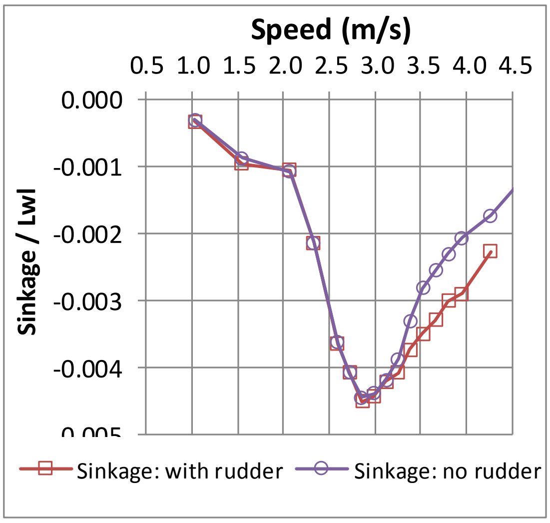

Figure 13 Effect of rudder on sinkage

The waves had amplitude of 20mm and wavelengths of 1.0m, 1.5m and 2.0m for Waves #1, #2, and #3 respectively. The results can be seen in Figure 14. The shorter wavelength waves have the larger effect with mean deltas over the speed range of 9.3% / 6.0% / 3.0% respectively. This plot emphasises the importance of measuring on a calm day, and also indicates the challenges which might be associated with the use of a towed probe to stimulate turbulence in a tank test.

5.2 FULL-SCALE OPEN-WATER TESTS

The data processing was more complex for the open water tests than for the tank tests. A number of practical issues had to be resolved. It was found that the anemometer and the wind vane did not appear to give reliable and accurate results. It was later discovered that the output voltage from the battery pack was reducing during the day, which affected the anemometer and wind vane data. Hence it was not possible to make the intended correction for windage. It thus became very important to average upwind and downwind runs in order to cancel any effect of the windage, even though the prevalent winds were light over the testing period.

The key challenge in the data analysis was to find segments of data for the two directions for which the speed matched sufficiently well. After some experimentation the criteria adopted for acceptance of the data segments was that the average speeds for the upwind and downwind segments of data should be different by less than 0.2 knots This criterion removed the majority of the outlier points (as well as several points which fitted the general trend very well). The remaining points are plotted in Figure 15, alongside the blockage-corrected tank data for the full-scale boat with rudder.

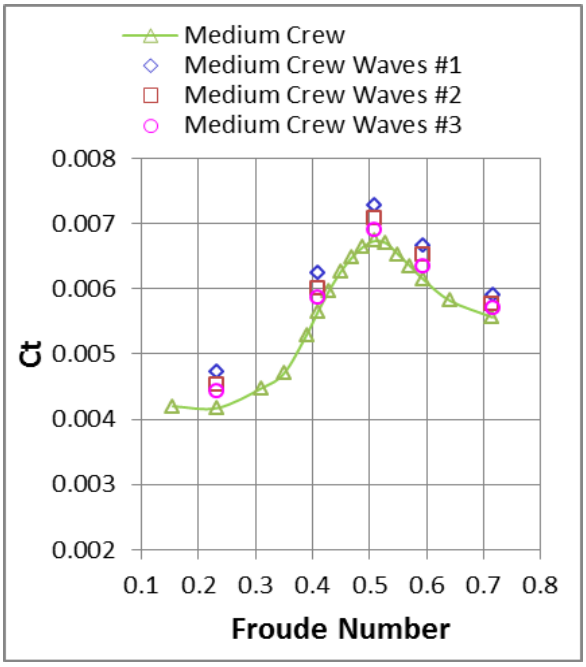

Figure 1 Full scale tank tests: Effect of waves

It can be seen that the general agreement is reasonably good over this speed range, although the points are more scattered than the data from the tank tests. For this reason the curve of the open water data is plotted as the best-fit sixth-order polynomial rather than the spline fit adopted for the tank data. The mean absolute error over the speed range between the tank test and the field test data is 3.2N, whilst the mean percentage error is 5.9%.

However this figure is skewed by large percentage errors at low speeds for which the total resistance is quite small; if the data points for the two lowest speeds are excluded from this calculation, then the mean percentage error between 2.0-4.0 m/s drops to 3.8%. The agreement is good at the higher speeds, where the influence of the blockage correction on the tank data is largest. This suggests that the blockage for the full-scale tank tests does not have a significant effect on the data, and that correction is working quite appropriately. It is also worth noting that the resistance values from the open water tests are generally slightly lower than those from the tank tests, so the influence of any small waves does not appear to be substantial in this data.

5.3 MODEL-SCALE TANK TESTS

Model-scale tests were conducted over the full speed range achievable in the tank. The data processing for the model scale data followed a standard process for resistance testing. A Prohaska test was carried out for the baseline case which yielded a form factor of 1.006. This was based on data from Froude Numbers between 0.15 and 0.2; at lower speeds there was some evidence of regions of laminar flow.

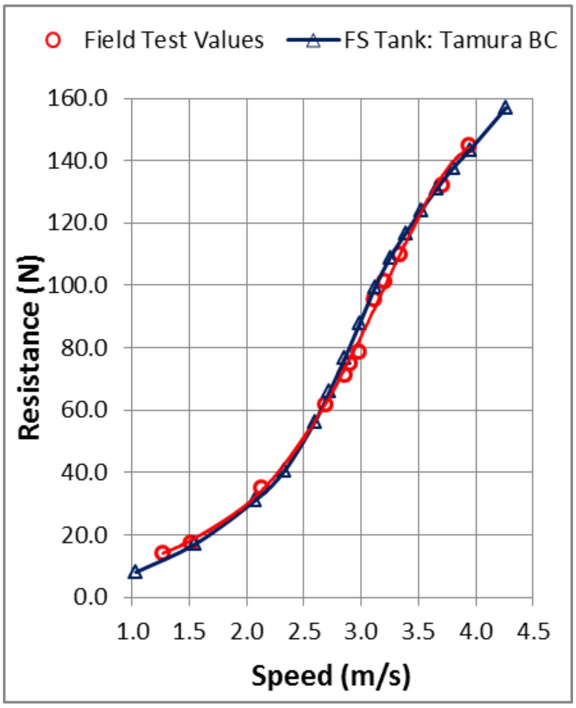

Figure 2 Full scale tests: Comparison of open water and tank tests (with rudder)

Model test data was decomposed in the standard fashion and extrapolated to full-scale using the ITTC 1957 correlation line. The static wetted area for each case was used for extrapolation, since no direct measurement of running wetted area was possible in these tests. Water temperature was corrected to 12.5 degree to match the full-scale tank tests. Repeatability over four repeats yielded a standard deviation of 0.23% of the mean.

The comparison between the resistance for the model-scale and full-scale tank tests is shown in Figure 16. It can be seen that the agreement is good up to a full-scale speed of about 3.0 m/s (corresponding to a Froude Number around 0.45), although the model-scale results are very slightly lower at the low speed. This suggests that there may be some influence of laminar flow due to the lack of turbulence stimulation. It was considered to attempt the use of a probe in front of the model as deployed by Viola & Enlander (2013); however the decision was made not to take this approach due to the impact of the generated waves on resistance, as shown in Figure 14. At higher speeds the curves diverge and the model tests predict a significantly lower resistance with a discrepancy up to around 10%. This is initially surprising; however some insight may be gained from Figure 17, showing the trim and sinkage comparisons for the same tests.

There are some slight discrepancies in sinkage at the lower speed range, but these occur when the measured sinkage is extremely small and could be due to measurement error and/or some “stiction” in the heave post in the towing set-up. Apart from this, both trim and sinkage values are quite close up to a full-scale speed of around 3.0m/s. However, for higher speeds the values diverge, with the model sinking less and exhibiting less bow-up trim.

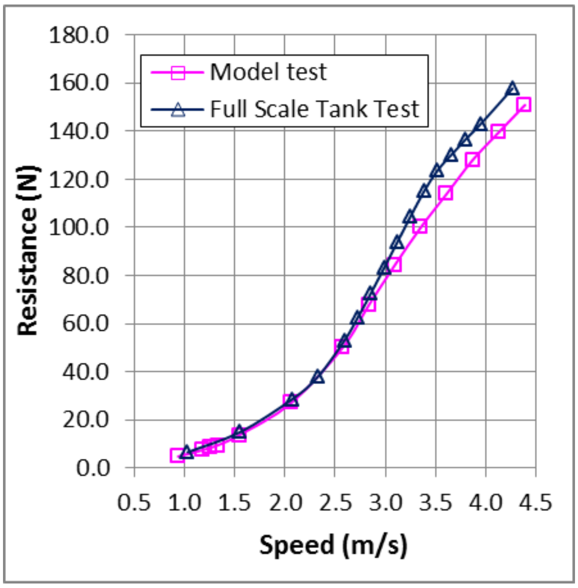

Figure 3 Resistance from full scale & model scale tank tests

The discrepancy starts to appear around the speed at which the sinkage starts to reduce as the model starts to plane. It is speculated that these differences in trim and sinkage may be at least part of the cause of the discrepancy in resistance.

6 DISCUSSION AND CONCLUSIONS

Hydrodynamic tests have been carried out using three different approaches for a high performance skiff dinghy: a moderate-scale model in a moderate-scale tank; a full-scale boat in a moderate scale tank, and a full scale boat on open water. The full-scale dinghy may also be considered as indicative of a large-scale model of a high-performance yacht.

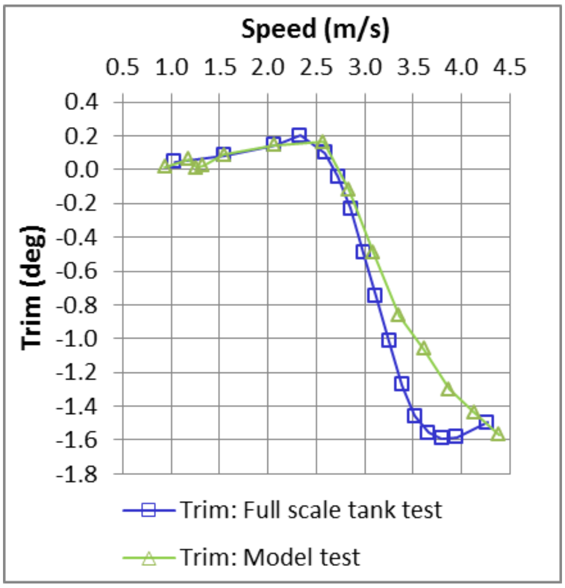

Figure 4 Tank Tests: Trim and sinkage from full scale and model scale tank tests

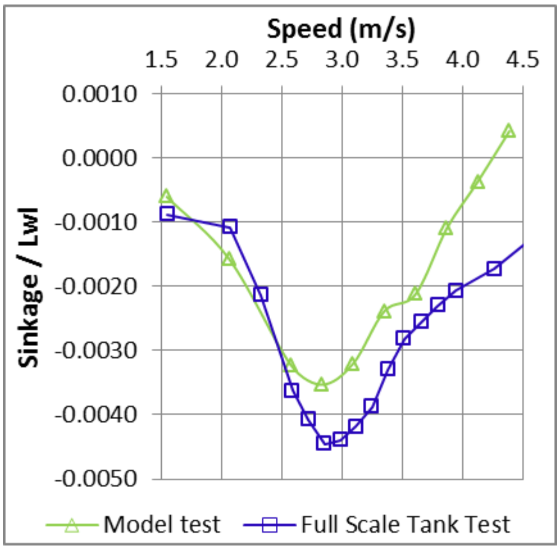

Figure 5 Tank Tests: Trim and sinkage from full scale and model scale tank tests

Agreement between the full-scale tests on open water and in the tank is promising, with an average error over the speed range of interest of just under 4%. Whilst this is certainly not as good as could be expected for a large scale tank test, it may well be adequate for early-stage or concept design studies, and could well be reduced through refinements in the approach. It is interesting to note that blockage in the tank does not appear to be a major issue in the speed range tested here of up to 4.5 m/s. This would correspond to over 20 knots if a 4.5m model represented a 30m yacht.

A number of approaches might be deployed to improve the quality of the measurements. A very simple improvement would be to use a voltage regulated power supply, and thus address the use of an inclinometer for trim measurements, and the anemometer and wind vane measurements of wind speed and direction more reliable. In order to improve the measurements at higher speed, the use of a more suitable tow boat, ideally with lower wash, would be helpful, while a better strategy for repeating speeds on upwind and downwind legs would allow the generation of larger data sets.

In the present test campaign only upright resistance was studied. However some preliminary trials were made of offset towing to simulate upwind sailing conditions and allow investigation of side force and induced drag, whilst also removing the dinghy from the wake of the tow boat. Some unexpected results were observed when testing the full-scale model with and without the rudder; the rudder was found to affect the trim and sinkage of the hull at higher speeds, which in turn affected the resistance.

The agreement between the model-scale results and the full-scale results in the tank is quite good at low speed, but surprisingly poor at higher speed. The model was built from lines supplied by the builder, and exhibited some differences of detail from the full-scale boat. It is speculated that the discrepancy in resistance at higher speeds may be due to these differences in the geometry particularly in respect of the sharpness of the chines.

It is intended to repeat the model-scale tests with the chines rounded in a manner similar to the full-scale boat, using an underwater camera to allow estimation of the running wetted surface area, and with a variety of turbulence stimulation approaches to shed more light on these issues.

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